



Panic-Based Overfishing in Transboundary Fisheries

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Accepted: 26 October 2018 / Published online: 14 November 2018
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Abstract

This paper analyses sustainability of bilateral harvesting agreements in transboundary fisheries. Harvesting countries obtain public and private assessments regarding their stock of fish, and the stock experiences ecological changes. In addition to biological uncertainty, countries may face strategic uncertainty. A country that receives negative assessments about the current level of fish stock, may become ‘pessimistic’ about the assessment of the other coastal state, and this can ignite ‘panic-based’ overfishing. The paper examines the likelihood of overfishing and suggests a unique prediction about the possibility of abiding by bilateral fishing agreements. Conditions under which the outcome of the asymmetric-information model reduces to the symmetric-information game are discussed, and optimal policy instruments for intergovernmental management of the stock are offered.

Keywords Regional Fisheries Management · Biological and strategic uncertainties · Equilibrium refinement · Global games · Risk dominance · Transboundary fishery · Ecological shifts

JEL Classification Q22 · Q28 · C73 · D82 · D83

1 Introduction

In 2013, 58% of the world’s assessed fish stocks were fully fished, with no potential for increase in production, and another 31% were overfished or depleted.¹ Furthermore, by estimating the stock of thousands of unassessed fisheries around the globe Costello et al.

¹ FAO yearbook (2016).

This paper was part of my Ph.D. thesis at the University of Edinburgh. I am grateful to my supervisors Jozsef Sakovics and Tim Worrall for their insightful guidance and comments. In addition, I thank the anonymous referees of the journal and Jonathan Thomas, Jakub Steiner, Rick van der Ploeg, Sabrina Eisenbarth, Stephen Blamey, Bipasa Datta and many conference participants at Wageningen (2013), SGPE at Crieff (2012, 2013), SURED (2014) and EEA-ESEM (2014) for their helpful comments and conversations. Furthermore, I thank SIRE for its financial support.

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(2012) revealed that 64% of marine fisheries have a stock below the maximum sustainable yield and that 18% of them are depleted.

According to Caddy's estimate in 1997, there are around 1000–1500 transboundary fisheries around the globe.² Given the tragic situation of the world's fisheries—especially because shared stocks are more prone to overexploitation or depletion (McWhinnie 2009)—studying this large number of fisheries that span over the countries is particularly important for policy making.

A possible way to manage such resources is through the formation of intergovernmental institutions, known as Regional Fisheries Management Organizations (RFMOs). However, in 2014, according to Barrett (2016), there were only 17 RFMOs, and only a subset of these covered transboundary fisheries. While some of the international fishery agreements have been successful, others have had challenging histories. An example of a fragile agreement is the Pacific Salmon Treaty between Canada and the United States in early 90s: a few years after the treaty was signed in 1985, the parties could not continue to abide by the agreed harvest shares due to climate variations, and they were on the verge of a fish war in 1993.³

In this paper, I develop a theoretical framework to understand the economic forces behind the decision-making of harvesting countries in the context of the international fishery agreements about transboundary resources. In other words, the framework assumes that the coastal states have agreed on a certain total allowable catch (TAC) and on a sharing rule under an international agreement; the focus of the paper is to examine whether the countries are able to comply with the agreement.

Countries normally have access to information about the assessment of fisheries. Sometimes the information is disseminated publicly. For example, international research institutions such as the Food and Agriculture Organization (FAO), Ransom A. Myers (RAM) Legacy, the International Council for Exploration of the Sea (ICES), the Northwest Atlantic Fisheries Organisation (NAFO) and the Forum Fisheries Agency (FFA) provide information in support of international agreements either globally or to their corresponding intergovernmental commissions and so to all involved coastal states. This paper assumes that the harvesters receive public information and, as in Roughgarden and Smith (1996) and Sethi et al. (2005), that estimates of the size of biomass have some measurement errors. This leads to 'biological' uncertainty in the decision-making of appropriators.

This paper takes two key observations into account. First, information on stock assessment can also be privately collected: countries today use more and more sophisticated assessment technologies to estimate the fish population, such as aquatic drones or sonar technologies. The main research question is how obtaining heterogeneous information about the health of fisheries affects the decisions of coastal states regarding compliance with their agreement. Private assessments,⁴ although highly correlated between countries, have an individual measurement error or noise. For the two countries in the model, the expected payoff of each country depends on its belief about the stock; but it also depends on 'higher-order beliefs': its belief about the other country's belief about the stock, its belief about the other country's belief about the country's belief about the stock, and so on. Thus this noisy private information leads to strategic uncertainty about the behaviour of the other harvesting country.

The second observation is about ecological variations and regime shifts in marine ecosystems. These regime shifts cause collapses of fisheries and can be both human-induced or

² By 'transboundary fisheries' I refer to the resources overlapping the 200-nautical-mile Exclusive Economic Zones of more than one country, which are shared as common-pool resources among some countries.

³ FAO Fisheries Report (2002).

⁴ Throughout the paper, assessment and signal are used as synonyms.

occur exogenously. Change of temperature and change of chemistry may be a result of waste, greater concentration of CO₂ in the water and plastic pollution, which all lead to a break in ecological web mechanisms, loss of resilience of ecosystems and a reduction in biodiversity across the world. This type of regime shift of marine fisheries, which is mainly due to the global-scale influence of human behaviour, is well-documented in science: to name a few, see Cheung et al. (2010), Berkes et al. (2006) and Folke et al. (2004). There are other types of ecological changes, which can be the result of physical variability. These factors, which can also lead to regime shift, are exogenous to humans' actions and have a more predictive trend. For examples, El Niño (which normally occurs every three to five years) and La Niña (occurring more frequently), lead to periodic variations of sea surface temperature in the Pacific Ocean and compound anthropogenic damage to coral reefs and a break in the food chain (Redondo-Rodriguez et al. 2012). Furthermore, Chavez et al. (2003) have proved the existence of multi-decadal regime shifts in the entire Pacific Ocean due to large-scale changes of thermal structure and oceanic circulations, where in each regime (that lasts around 25 years) the population of either anchovies or sardines becomes dominant and the biomass of the other species collapses.

This paper uses a model in which the fishery is threatened both by harvesting activities of the countries and the exogenous ecosystem factors. An example of this is that the population of capelin fish in the Barents Sea has collapsed twice in 20 years due both to overexploitation and to multi-species-ecosystem effects (Hjermann et al. 2004). Thus the model focuses on a fishery which undergoes a catastrophic situation of depletion at a certain point in the future, as the result of ecological factors. Specifically, a two-period model is presented, while the setup also deals with the possibility of countries' triggering the catastrophe at an earlier date. The results of this model help a potential (intergovernmental) manager of the stock to explain the economic rationale of overfishing and the driving forces of the early collapse of such fisheries.

I model the interaction of countries in a coordination setup: that is, payoffs are strategic complements. While coordination and trust play a crucial role in environmental economics, coordination models with perfect information typically have multiple equilibria, reducing the predictive power of the models. The first equilibrium selection technique suggested in this paper is the risk-dominance criterion of Harsanyi and Selten (1988). This criterion implies the selection of less risky actions and leads to a unique equilibrium strategy under precise public and private information.

For the game of incomplete information, where assessments are noisy, another equilibrium-refinement technique is studied. As the private information becomes 'almost precise' (although the level of the stock will never be common knowledge), the coordination game will inevitably have the unique equilibrium of 'global games' in Carlsson and Van Damme (1993) and Morris and Shin (1998). Global games is terminology chosen by Carlsson and Van Damme (1993) to refer to games of incomplete information with strategic complementarities in payoffs, where as a result of receiving almost precise private correlated signals about the underlying state variable, the game has a unique prediction. In Sect. 5 there is a discussion of the proposition that if the private information is almost precise, rationality inevitably enforces the unique equilibrium of global games; thus this equilibrium-refinement criterion is not an arbitrary choice.

The resultant unique equilibrium helps the researcher or the potential manager of the resource to derive a conclusion about the interaction of the harvesting agents, and to find the likelihood of overfishing at each level of (the assessment about) the stock.

In addition, as the global-game equilibrium threshold coincides with the risk-dominant threshold in the precise-signal game,⁵ it provides a tractable framework for policy implications in common-property fisheries. Indeed, one of the contributions of this paper is using the equilibrium-uniqueness results to derive optimal levels of policy-related parameters: over-fishing cost and the TAC of transboundary fisheries.

The structure of the paper is as follows: the related literature is reviewed in Sect. 2; the model is introduced in Sect. 3; next, in Sect. 4 the model is analysed under precise assessments and the risk-dominance equilibrium refinement is discussed; then, in Sect. 5 by assuming imprecise assessments the model is examined under biological and strategic uncertainties, and the global-game equilibrium refinement is introduced; the conclusion is in Sect. 6 and extended proofs are provided in Appendix.

2 Related Literature

The literature on game theory and fisheries is surveyed by Munro (2009), Bailey et al. (2010), Van Long (2011), Hannesson (2011) and Miller et al. (2013). This paper is related to two main strands of the literature of common-property natural resources (CPNR): stochastic resource games and the literature on regime shifts (or catastrophes).

The seminal papers in the area of stochastic resource games are Reed (1978, 1979), where he introduced stochastic fluctuations in the stock recruitment of a renewable resource.⁶ Since then the role of biological uncertainties and imperfect information has been extensively studied. In contrast to biological uncertainty, strategic uncertainty and incomplete information has been given less attention in the theoretical literature of CPNR. There are a few authors who examine the role of asymmetric information: Laukkanen (2003, 2005) and Tarui et al. (2008) investigate situations where the harvesting actions (of one or all players) can be private information. They characterise the set of subgame perfect equilibrium payoffs that can be sustained given the threat of reversion to the non-cooperative or worst equilibrium harvest. The focus of the model considered in this paper is the effect of observing noisy private signals about the state of the fishery on second-guessing the assessment of the other coastal state. Furthermore, instead of deriving the set of sustainable harvests in repeated-game and imperfect-monitoring settings, here a coordination game is studied where the existence of private information may contribute to equilibrium refinement.

In addition, McKelvey et al. (2003) and Golubtsov and McKelvey (2007) study fishery games where the fishing fleets observe private noisy signals about the stock growth and stock-split parameters. Using simulations and assigning numeric precisions to the signals, they compare the outcome of cooperative and non-cooperative harvest strategies. Here we derive analytical solutions to the problem.

The second strand is the extensive literature on the effect of risk of adverse events which cause a regime shift. This literature, which includes either control theory or coalition formation studies, is reviewed by Crépin et al. (2012), Barrett (2013), Ren and Polasky (2014) and van der Ploeg (2014). Polasky et al. (2011) classify these models into two groups, where either system dynamics admits a fixed point or the underlying stock has an exogenous threshold (or tipping point). This paper instead can be classified under a third group of economic models

⁵ The equivalence of the risk-dominant and the global-game equilibria was first proved by Carlsson and Van Damme (1993) for the class of static 2×2 games.

⁶ To name a few pioneers of stochastic resource games, see Spulber (1982, 1985), Mirman and Spulber (1985), Clark and Kirkwood (1986), Clemhout and Wan (1985), Clarke and Reed (1994) and Roughgarden and Smith (1996).

of regime shift, where the binary action of players and their monotone expected payoffs lead to an equilibrium that takes a threshold form with respect to the underlying state variable, the fish stock. I construct a model to explain the regime shift to depletion as a result of two factors. First, the effect of ecological factors is modelled as an exogenous tipping point at the end of the second period, and secondly, the threshold behaviour of coastal states at an early stage of the game may cause a regime shift. This later threshold is endogenous, and enables us to derive a comparative-static analysis of it.

The present paper contributes to the strand in the literature that deals with equilibrium refinement. The multiplicity of equilibria has been intensively investigated in the literature of CPNR.⁷ Coordination games are important settings in CPNR, but they face the problem of multiplicity of equilibria. Parkhurst et al. (2002), Parkhurst and Shogren (2007) and Banerjee et al. (2014) examine the effect of an ‘agglomeration bonus’ to save endangered species in coordination games, and they suggest experimental evidence for equilibrium selection. Although equilibrium refinement has been one of the main challenges of game theory since the 1980s, to the best of my knowledge equilibrium selection in coordination games has not been addressed explicitly in the theoretical literature on CPNR.

Here, I construct a coordination resource game, where the application of the risk-dominance criterion of Harsanyi and Selten (1988) or the global-game equilibrium-selection of Carlsson and Van Damme (1993) cause the equilibrium to be unique. In global games, improved precision of the private information of players confronting a coordination game leads to a unique prediction about their behaviour. An example of experimental support for the theory of global games can be found in Heinemann et al. (2004).

3 The General Framework

In each period a 2×2 game with *stay-exit* structure is played.⁸ Two countries share a stock of fish $\omega_t \in (0, 1)$, where subscript t refers to time. They choose between two actions: *sustainable-fishing*, S , and *overfishing*, O . Conventionally, ‘sustainable’ yield means a level of catch such that the stock remains constant over time; however in this paper, henceforth, I define sustainable catch as harvesting in compliance with a pre-agreed TAC and sharing rule, while overfishing is depleting the resource. By ‘stay-exit’ structure I mean that if the countries decide to maintain the resource then the game will continue to the next period, but they may choose to exhaust the stock in any period and end the game.

If there is no uncertainty in the environment and the stock of fish is uninterrupted, then it grows according to the commonly-used growth function of Levhari and Mirman (1980): an increasing, strictly concave and bounded growth function,

$$\omega_t = (\bar{\omega}_{t-1})^\alpha \quad (3.1)$$

where $0 < \alpha < 1$ is the reproduction parameter, and $\bar{\omega}_{t-1} \in (0, 1)$ is the escapement level of the stock at the end of period $t - 1$, and $\bar{\omega}_0$ is the initial stock, which is chosen by nature. We are abstracting from the possibility of depensation, and although the reproduction rate is low at small levels of the stock, ω_t is increasing in such levels. Furthermore, α and the growth

⁷ Most notably, Dutta (1995) generalised the Folk Theorem of Aumann and Shapley (1994) to stochastic games, and Benhabib and Radner (1992), Dutta and Sundaram (1993), Dockner and Sorger (1996) and Sorger (1998) show a multiplicity of perfect equilibria in deterministic dynamic games.

⁸ This is similar to the theoretical global game paper of Chassang (2010). In contrast to his model, where the state variable is i.i.d. in this paper, as a renewable resource, the state of a fishery depends on its previous value through the growth function.

function are common knowledge between the harvesting countries. However, in this model the coastal states face uncertainties about both the stock of fish and the harvesting action of the other player. Therefore, the stock of fish, Ω_t , is a state variable.⁹

The timing of the game is as follows. At the beginning of the game, nature chooses the state of the fishery, $\bar{\omega}_0$. Then at the beginning of each period t , for $t \in \{1, 2\}$, the escapement level, $\bar{\omega}_{t-1}$, which is the remaining biomass left from the previous period, reproduces, and the countries receive a public signal about the state of the fishery,

$$y_t = \omega_t + \theta_t \quad (3.2)$$

where ω_t is in fact the population of fish in the stock stated in Eq. (3.1), and θ_t captures a measurement error in the public assessment, which I model as an additive noise to the stock of the transboundary fishery. Furthermore, $\Theta \sim U[-c, c]$, where $0 < c < 1$ and $U[\cdot]$ is the uniform probability density function.¹⁰ The noise of public signals are serially uncorrelated and independent of ω_t . Parameter c refers to the precision of public signal and the assessment errors lead to biological uncertainty.

In addition, in every period $t \in \{1, 2\}$ and before any decision making, country i obtains, as a result of its own independent research, a noisy private signal, x_t^i , about the size of the stock, where

$$x_t^i = \omega_t + \varepsilon_t^i \quad (3.3)$$

and $\varepsilon \sim U[-a, a]$ and $0 < a < 1$. The superscript $i \in \{1, 2\}$ is a country's index, and later $-i$ will refer to the other country. Here ε_t^i can be interpreted as the private measurement error in the assessment of fish stock, and parameter a indicates the precision of private information. These noises are i.i.d. and independent of ω_t . Although the signals of the two countries are highly correlated, they are private information. The structure of payoffs, the distributional assumptions of the private signals and the noise technology of the state of the fishery defined in Eqs. (3.2) and (3.3) are common knowledge among the countries. It is assumed that X_t , Y_t and Ω_t map into $(0, 1)$. This is because the stock variable must be non-negative and also, the growth of stock occurs only in the range $(0, 1)$. See Assumption 1 in Appendix 7.1 for more details. Furthermore, there is no assumption regarding the order in which the signals are received.

After the acquisition of information, the players choose between the two harvesting levels simultaneously. In period $t \in \{1, 2\}$, when the countries are making decisions the true level of stock is ω_t , and at this interim stage the coastal states do not observe each other's harvesting decision in the period t . Finally, at the end of each period, actions are observed and payoffs are determined.¹¹ At the end of the second period, the fishery reaches an ecological tipping point, and collapses. The two periods represent two long periods, followed by the ecological regime shift.

The stay-exit structure implies that, if in the first period the players coordinate on sustainable-fishing, then the game continues to the next period, and if one or both countries overfish in any period, the game ends, both players receive the termination payoffs of that period, the biomass is reduced to a level below the minimum viable fish population, and the fishery can never recover. This assumption implies that we focus on the stationary subclass of transboundary fisheries, which do not have a migratory pattern.

⁹ Henceforth, upper-case letters denote random variables, and lower-case letters denote the realised values that the random variables map onto. Table 7.6 summarises all the notation in the paper.

¹⁰ In Appendix 7.5 the assumption of uniform distributions is relaxed.

¹¹ I refer to the framework described as a two-period model, since $t = 0$ is just used for the sake of completeness and defining the initial values. So, the first period is when $t = 1$.

Table 1 Normal-form representation of the game in the first period under the assumption of precise information, and without the continuation payoffs

		Country 2	
		S	O
Country 1	S	$r\omega_1, r\omega_1$	$r\omega_1, (1-r)\omega_1 - \frac{\kappa}{\omega_1}$
	O	$(1-r)\omega_1 - \frac{\kappa}{\omega_1}, r\omega_1$	$\frac{\omega_1}{2} - \frac{\kappa}{\omega_1}, \frac{\omega_1}{2} - \frac{\kappa}{\omega_1}$

Table 1 depicts the payoffs of the first period (without continuation values) under an assumption of precise information, i.e. $x_1^i = y_1 = \omega_1$. The payoff of the sustainable harvesting is equal to the countries' yield or the amount of fish that they harvest according to the pre-committed TAC with harvest fraction r for each country, and $r \in (0, \frac{1}{2})$. At the moment this fraction is exogenously fixed,¹² and if both countries choose the sustainable harvest, then they share the TAC, $2r$, symmetrically. Also, a country choosing a harvest strategy is assumed to be able to enforce it at a national level by managing and regulating its own fishing fleets.

Given that this is not an open-access fishery, by breaking the bilateral agreement in the first period, the deviating country bears a cost, $\frac{\kappa}{\omega_1}$, where κ is a positive constant. This captures the extra costs of illegal harvesting imposed on any party that prevents the realisation of continuation payoffs. In other words, it is assumed that public awareness about breaching the agreement and loss of biodiversity leads to international pressure about resource conservation, which negatively affects the payoff of the overfishing state. This may include reputational loss or judicial costs of resolving the issue nationally or internationally.

This cost is modelled to be negatively related to the size of fish population. The existence of such an overfishing cost in the first period implies that if the fishery is small in size (where the growth rate is increasing), overfishing causes a larger loss for the future generations of fish, so that there is more public outcry and international pressure to protect it. Conversely, if the population of the biomass is close to its upper bound, then it would not have a large potential for growth in the next period, and this reduces the international conservation incentive and hence the overfishing cost. Sensitivity of the results to this cost and its specific functional form is discussed for the model with precise signals in Sect. 4, and for the model with imprecise assessments in Sect. 5.

The payoff of (O, S) and (S, O) in Table 1 refer to miscoordination situations where one party fishes sustainably and the other party harvests the remaining stock of fish and bears the overfishing cost. The payoff of (O, O) in the first period is sharing the resource equally minus the overfishing cost. Furthermore, it is implicitly assumed that the price of fish is normalised to one, and there is no market externality. In addition, the cost of acquiring information is normalised to zero. These simplifying assumptions provide us with a tractable model to study the strategic interaction of countries in the transboundary fisheries.

Due to the ecological regime shift there is no continuation value in the last period, and so there is no overfishing cost either. The strictly dominant strategy for both players is overfishing. Hence, given the symmetry of the game, they share the stock equally in the last period. Appealing to sequential rationality, by backward induction, the first period of the two-period model is analysed as a one-shot game augmented with the continuation payoff of a dominant action in the second period. Due to the stay-exit structure, in the first period of a two-period game, there is no continuation value if at least one of the countries chooses overfishing in the first period. The countries receive a positive payoff in the second period

¹² In Sect. 5.4, the optimal harvest fraction as an endogenous variable from the continuum set of r is derived.

only if both of them abide by the agreed TAC in the first period. Hence, the total payoff of country i in the first period of a two-period game by playing (S, S) is

$$r\mathbb{E}[\omega_1|y_1, x_1^i] + \frac{\beta}{2}\mathbb{E}[\omega_2|y_1, x_1^i, \sigma_1^1 = \sigma_1^2 = 1] \quad (3.4)$$

where $\beta \in (0, 1)$ is the discount factor, which is identical for both harvesting agents, and $\mathbb{E}[\cdot]$ is the expectation operator. Furthermore, σ_t^i is the strategy of country i in period t , such that $\sigma_t^i : X_t \times Y_t \rightarrow [0, 1]$, and the range $[0, 1]$ refers to the probability of sustainable fishing by country i given its signals.

This setup fits into the literature of stochastic games, where the evolution of stock depends on both the actions and the random state variable. The stochastic resource game explained can be denoted by $G(\bar{\omega}_0, a, c, r, \alpha, \beta, \kappa)$, and henceforth I suppress notation and express it as G .

By definition, a strategy σ_t^i is monotone if the expected payoff of country i is monotone in its assessment. Furthermore, a strategy σ_t^i is a threshold strategy if there exists a critical level of (assessment of) the fish stock below which the countries sustainably harvest and above which they overfish. The reason for defining the threshold strategies with sustainable fishing for low levels of stock is the concavity of the growth function and the existence of overfishing cost. These lead to greater conservation incentives where the biomass is small. Finally, since the game is symmetric, the ‘equilibrium’ will in fact refer to a pair of equilibrium strategies.

4 Precise Assessments

In this section I examine the decision of countries in the first period, under the assumption of precise public and private signals, i.e. $x_1^i = y_1 = \omega_1$ for both i . In other words, in equilibrium there is complete and perfect information about the action of the other country, and the current state of the fishery.

Given game G with payoffs depicted in Table 1 and taking into account the continuation payoffs, the countries compare the expected payoff of sustainable fishing versus overfishing in the first period. Let us define two functions:

$$\underline{\Delta}^0(\omega_1) \equiv r\omega_1 + \frac{\beta}{2}\mathbb{E}[\omega_2|\omega_1, \sigma_1^1 = \sigma_1^2 = 1] - (1-r)\omega_1 + \frac{\kappa}{\omega_1} \quad (4.1)$$

$$\bar{\Delta}^0(\omega_1) \equiv r\omega_1 - \frac{\omega_1}{2} + \frac{\kappa}{\omega_1} \quad (4.2)$$

where $\underline{\Delta}^0(\omega_1)$ represents the difference of expected payoff of sustainable harvest and overfishing for country i , given that country $-i$ chooses sustainable harvest. Similarly $\bar{\Delta}^0(\omega_1)$ is the expected payoff differential of a country given that the other country chooses overfishing. Superscript 0 refers to the precise-signal case. Note that here simply, $\mathbb{E}[\omega_2|\omega_1, \sigma_1^1 = \sigma_1^2 = 1] = (1-2r)^\alpha(\omega_1)^\alpha$. For ease of exposition, let $b \equiv (1-2r)^\alpha$, which captures the grown total escapement fraction in the second period.

4.1 Dominance and Intermediate Regions

There is a low level of fish population, $\underline{\omega}_1$, below which sustainable harvest is a dominant action. This is due to the high overfishing cost and the increasing reproduction rate of the fishery at low levels of the stock. I call $(0, \underline{\omega}_1)$ the ‘lower dominance region’ (LDR), where

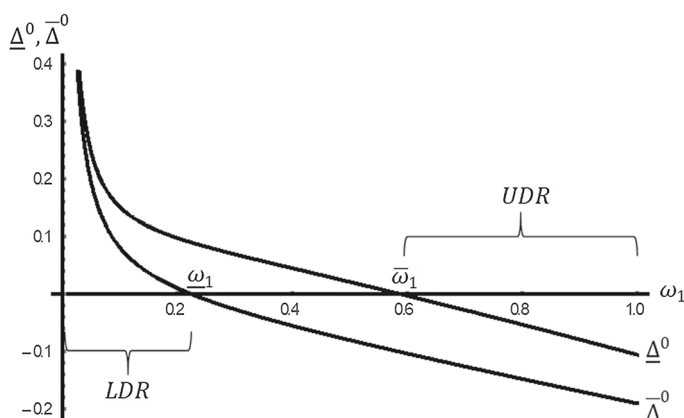


Fig. 1 $\underline{\Delta}^0(\omega_1)$ and $\bar{\Delta}^0(\omega_1)$, where $\beta = 0.9$, $\kappa = 0.01$, $r = 0.3$, and $\alpha = 0.5$, then $\underline{\omega}_1 = 0.22$ and $\bar{\omega}_1 = 0.58$

$\underline{\omega}_1$ solves $\bar{\Delta}^0(\underline{\omega}_1) = 0$. In other words, for any $\omega_1 \in (0, \underline{\omega}_1)$, independent of the action of the other country, the payoff of sustainable extraction is strictly larger than overfishing, i.e. $\underline{\Delta}^0(\omega_1) > 0$ and $\bar{\Delta}^0(\omega_1) > 0$.

Similarly, there exists an ‘upper dominance region’ (UDR), $(\bar{\omega}_1, 1)$, where overfishing in the first period is a dominant action.¹³ In this region, there is no rationale for waiting until the next period. At the threshold, $\underline{\Delta}^0(\bar{\omega}_1) = 0$, and for any $\omega_1 > \bar{\omega}_1$, $\underline{\Delta}^0(\omega_1) < 0$ and $\bar{\Delta}^0(\omega_1) < 0$.

Figure 1 depicts a numeric example of $\underline{\Delta}^0(\omega_1)$ and $\bar{\Delta}^0(\omega_1)$, where $\underline{\omega}_1$ and $\bar{\omega}_1$ show the boundaries of the LDR and UDR, respectively.

This leads to the existence of an intermediate region of fish population, $[\underline{\omega}_1, \bar{\omega}_1]$, in which there is no dominant action. The continuation payoff and the overfishing cost are such that the game in the first period is a coordination game, i.e. $\underline{\Delta}^0(\omega_1) \geq 0$, with equality at $\bar{\omega}_1$ and $\bar{\Delta}^0(\omega_1) \leq 0$, with equality at $\underline{\omega}_1$. Therefore, in this region, on which I focus, the game has two pure Nash equilibrium actions of (S, S) and (O, O) .

To characterise this region, it is sufficient to solve for $\underline{\omega}_1$ and $\bar{\omega}_1$. Solving $\bar{\Delta}^0(\underline{\omega}_1) = 0$ implies $\underline{\omega}_1 = \sqrt{\kappa/(\frac{1}{2} - r)}$. Similarly, $\bar{\omega}_1$ solves $\underline{\Delta}^0(\bar{\omega}_1) = 0$. There is no explicit solution for $\bar{\omega}_1$, but note that $\underline{\Delta}^0(\omega_1)$ is continuous in ω_1 , also $\lim_{\omega_1 \rightarrow 0} \underline{\Delta}^0(\omega_1) = +\infty$. I assume $\underline{\Delta}^0(\omega_1)$ is strictly monotone and it has a unique real root between $(\underline{\omega}_1, 1)$. This assumption is explicitly expressed in Assumption 2 in “Appendix 7.1”.

Given Assumption 2, there exist a unique real root, $\bar{\omega}_1 \in (0, 1)$, solving $\underline{\Delta}^0(\bar{\omega}_1) = 0$. Finally, I need to assume $\underline{\Delta}^0(\underline{\omega}_1) > \bar{\Delta}^0(\underline{\omega}_1)$, to guarantee that $\underline{\omega}_1 < \bar{\omega}_1$. See Assumption 3 in “Appendix 7.1”. Intuitively, in the LDR sustainable harvest is a cooperative action and increases the conservation incentive of the other country.

Therefore, $0 < \underline{\omega}_1 < \bar{\omega}_1 < 1$, and thus game G admits LDR and UDR, and it also admits an intermediate region of fish population in between. Hence in the intermediate region, where there is no dominant action, sustainable harvest may be a pure equilibrium action and the countries may choose to wait in the first period. This is because the fish stock is reproducing and there is a considerable overfishing cost.

¹³ The terminology of LDR and UDR are borrowed from the literature on global games. As is discussed in Sect. 5, their existence provides a sufficient (but not necessary) condition for the equilibrium refinement.

By mixing, depending on weights that are assigned to the action of the other player, the expected payoffs shift. Thus, the set of Subgame Perfect Equilibria (SPE) admits a continuum of threshold equilibria on $[\underline{\omega}_1, \bar{\omega}_1]$, where $\bar{\Delta}^0(\omega_1) > 0$ and $\underline{\Delta}^0(\omega_1) < 0$. In the ‘most cooperative equilibrium’, the coastal states’ expected payoffs admit a threshold on $\bar{\omega}_1$, implying that with probability one both countries sustainably harvest on the entire intermediate region in addition to the LDR. This resembles the Pareto efficient equilibrium. Conversely, $\underline{\omega}_1$ is the ‘least cooperative equilibrium’ threshold, where the coastal states sustainably harvest only in the LDR.

Despite the fact that in the dominance regions there are unique outcomes, for any state of the fishery in between the upper-bound and lower-bound thresholds there is a multiplicity of equilibrium outcomes such that the players either play (O,O) or (S,S) or randomise (at the thresholds). Therefore, if there is complete information about the current stock of fish, then the theory cannot predict the action of harvesting agents. This multiplicity of equilibrium outcomes, which is a natural characteristic of coordination games under precise information, reduces the predictive power of the model to zero in the absence of any equilibrium refinement, for any value of the stock $\omega_1 \in [\underline{\omega}_1, \bar{\omega}_1]$.

4.2 Equilibrium Refinement with Precise Assessments

A relevant equilibrium-selection technique in this game with precise information is the risk-dominance criterion of Harsanyi and Selten (1988). In the first period of any game G , sustainable-fishing weakly risk-dominates overfishing if the product of deviation losses of sustainable-fishing is weakly greater than those of overfishing, i.e.

$$\left[r\omega_1 + \frac{\beta}{2} \mathbb{E}[\omega_2 | \omega_1, \sigma_1^1 = \sigma_1^2 = 1] - (1-r)\omega_1 + \frac{\kappa}{\omega_1} \right]^2 \geq \left[\frac{\omega_1}{2} - \frac{\kappa}{\omega_1} - r\omega_1 \right]^2 \quad (4.3)$$

The terms inside the brackets are $\Delta^0(\omega_1)$ in (4.1) and negative of $\bar{\Delta}^0(\omega_1)$ in (4.2), respectively. As explained, in the dominance regions, there exists a unique prediction; therefore I will focus on the intermediate region. For any $\omega_1 \in (\underline{\omega}_1, \bar{\omega}_1)$ any game G is a coordination game, i.e. (S,S) and (O,O) are pure Nash equilibria of the game; thus both expressions inside the brackets in (4.3) are positive in this region. Furthermore, a fish population equal to the upper-bound threshold, $\bar{\omega}_1$, does not satisfy the risk-dominance criterion in (4.3). Hence, for any $\omega_1 \in [\underline{\omega}_1, \bar{\omega}_1]$, by taking the square root of both sides of (4.3), the condition can be written as $\Delta^{RD}(\omega_1) \geq 0$, where

$$\Delta^{RD}(\omega_1) \equiv 2r\omega_1 + \frac{\beta}{2}b(\omega_1)^\alpha - (1-r)\omega_1 + \frac{2\kappa}{\omega_1} - \frac{\omega_1}{2} \quad (4.4)$$

Proposition 1 *In the first period of any game in G , under precise signals, there exists a unique symmetric risk dominance threshold, ω^{RD} , below which sustainable harvest is risk-dominant and above which overfishing is risk-dominant.*

The proof is in Appendix 7.2, and Fig. 2 provides a numeric illustration of the unique threshold.

According to Harsanyi and Selten (1988), if the players coordinate on the less risky action, then the risk-dominance equilibrium-selection criterion provides a unique prediction. However, it is known that in a model with precise information, the selection of an equilibrium refinement criterion is post-hoc. For example one could choose the Pareto-efficient equilibrium, where the players coordinate on the most cooperative equilibrium and harvest

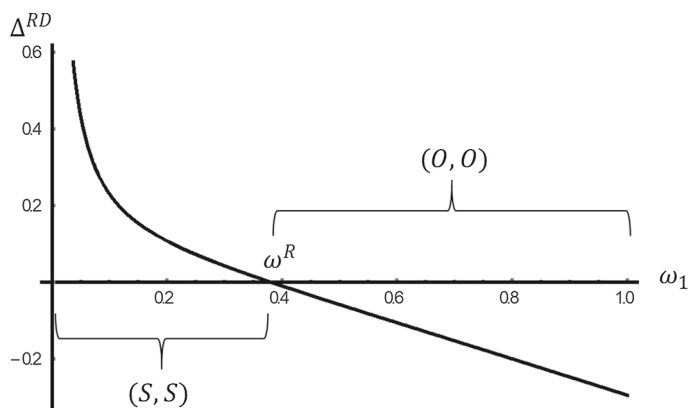


Fig. 2 Risk-dominant threshold and uniqueness of equilibrium actions for each level of the fish stock, where $\beta = 0.9$, $r = 0.3$, and $\alpha = 0.5$ and $\kappa = 0.01$, then $\omega^{RD} = 0.38$

sustainably for any level of stock up to $\bar{\omega}_1$. It is not immediately clear why we can expect the harvesters to behave according to any of these criteria. However, as is discussed in 5.3, the global game provides a justification for the risk-dominance selection.

4.3 Comparative Statics on the Upper-Bound, Lower-Bound and Risk-Dominance Thresholds

The discount factor, β , and the reproduction parameter, α , through the channel of the continuation value of sustainable harvest, affect $\underline{\Delta}^0(\omega_1)$ but not $\bar{\Delta}^0(\omega_1)$. If the countries become more patient, i.e. the discount factor increases, or if the reproduction parameter, α , decreases (implying a more concave growth function), then for any given level of fish population, $\underline{\Delta}^0(\omega_1)$ shifts up, and so its crossing, $\bar{\omega}_1$, moves to the right. Therefore, there would be a smaller UDR, while ω_1 is constant.

The sensitivity of $\Delta^{RD}(\omega_1)$ and therefore ω^{RD} to the discount factor and reproduction parameter are similar to $\underline{\Delta}^0(\omega_1)$ and $\bar{\omega}_1$. Thus as β increases, or as α decreases, ω^{RD} shifts to the right, so that in a larger set of fish population the unique action of sustainable extraction is risk dominant. The result regarding the negative relation of the reproduction rate and the likelihood of overfishing, is in line with the empirical study of McWhinnie (2009), which shows that stocks that have a slower growth are more prone to overexploitation.

However, the overfishing cost parameter, κ , and the harvest fraction, r , affect both ω_1 and $\bar{\omega}_1$, and hence ω^{RD} . These two parameters are important potential policy instruments, and in Sect. 5.4, we derive the optimal level of these policy parameters. In the conclusion, moreover, we provide some suggestions regarding these instruments for RFMOs.

Since

$$\frac{\partial \underline{\Delta}^0(\omega_1)}{\partial \kappa} = \frac{\partial \bar{\Delta}^0(\omega_1)}{\partial \kappa} = \frac{1}{\omega_1} \quad (4.5)$$

increasing the cost parameter, shifts both ω_1 and $\bar{\omega}_1$ to the right. Hence, by expanding the LDR and shrinking the UDR, a larger overfishing cost implies a safer fishery on average.¹⁴

¹⁴ However, there is no prediction about the equilibrium selection by the harvesting countries in the intermediate region.

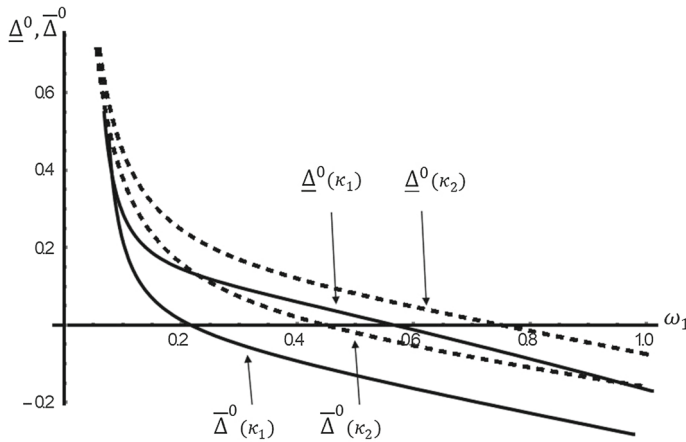


Fig. 3 Effect of a change in the overfishing cost on the LDR and UDR, where $\beta = 0.9$, $r = 0.3$, and $\alpha = 0.5$. Solid lines show $\underline{\Delta}^0$ and $\bar{\Delta}^0$ if $\kappa_1 = 0.01$. Dashed lines represent these functions if $\kappa_2 = 0.04$

Figure 3 illustrates this result with a numeric example. Given the assumed parameters, if the overfishing cost parameter is $\kappa_1 = 0.01$, then $\underline{\omega}_1(\kappa_1) = 0.22$ and $\bar{\omega}_1(\kappa_1) = 0.58$. By increasing the cost to $\kappa_2 = 0.04$, and hence the shift of $\underline{\Delta}^0$ and $\bar{\Delta}^0$ to the right, these thresholds are increased to $\underline{\omega}_1(\kappa_2) = 0.44$ and $\bar{\omega}_1(\kappa_2) = 0.74$.

Furthermore, because $\frac{\partial \Delta^{RD}(\omega_1)}{\partial \kappa} = \frac{2}{\omega_1}$, ω^{RD} is more sensitive relative to $\underline{\omega}_1$ and $\bar{\omega}_1$ thresholds to the changes in overfishing cost. Hence, when κ increases, all three thresholds shift to the right, but ω^{RD} responds more, which implies coordination on the conservation action for a larger range of fish population. Without the overfishing cost, i.e. if $\kappa = 0$, there would be no LDR, and $\Delta^{RD}(\omega_1)$ would be a hump-shape function, though it still admits a single positive real root at ω^{RD} , and at any level of the stock above ω^{RD} , $\Delta^{RD}(\omega_1) < 0$, and below it, $\Delta^{RD}(\omega_1) > 0$. Therefore, proposition 1 would hold. This shows the main reason that the countries abide by the agreement at low levels of the stock is the concave-growth assumption; and again this is consistent with McWhinnie (2009). Furthermore, with any other functional form for the overfishing cost, the risk-dominance criterion leads to a unique monotone equilibrium, as long as the single-crossing property and the mentioned signs of $\Delta^{RD}(\omega_1)$ hold. Clearly, a cost function which is negatively related to the stock, provides monotonicity of $\Delta^{RD}(\omega_1)$ as well.

Finally, because $\frac{\partial \bar{\Delta}^0(\omega_1)}{\partial r} = \omega_1$, if the countries agree on a larger TAC, and hence if r increases, then $\underline{\omega}_1$ increases, so that, up to a larger level of fish population, the sustainable extraction is a dominant action. However, because

$$\frac{\partial \underline{\Delta}^0(\omega_1)}{\partial r} = 2\omega_1 - \alpha\beta(1-2r)^{\alpha-1}\omega_1^\alpha \quad (4.6)$$

can be either positive or negative, and $\frac{\partial^2 \underline{\Delta}^0(\omega_1)}{\partial r^2} < 0$, $\underline{\Delta}^0(\omega_1)$ is not monotone in r , and there is a trade off. Increasing the harvest fraction of sustainable catch on the one hand reduces the continuation payoff, $r\omega_1 + \frac{\beta}{2}b\omega_1^\alpha$, and on the other hand reduces the temptation for unilateral deviation $(1-r)\omega_1$. Indeed, there is a critical harvest fraction, $\bar{r} = \frac{1}{2} - (\frac{\alpha\beta}{2})^{\frac{1}{1-\alpha}} \frac{1}{2\omega_1}$, which solves $\frac{\partial \underline{\Delta}^0(\omega_1)}{\partial r} = 0$, and below which increasing the shares of sustainable fishing reduces the temptation for overfishing, so that for any level of fish stock, $\underline{\Delta}^0(\omega_1)$ shifts up, pushing $\bar{\omega}_1$

to the right. Increasing the shares beyond the critical \bar{r} , decreases the upper-bound threshold as it reduces the continuation payoffs.

As expected, neither does the risk-dominance threshold respond monotonically to the harvest fraction, and solving

$$\frac{\partial \Delta^{RD}(\omega_1)}{\partial r} = 3\omega_1 - \alpha\beta(1 - 2r)^{\alpha-1}\omega_1^\alpha = 0 \quad (4.7)$$

implies the existence of a critical harvest fraction, $r^{RD} = \frac{1}{2} - (\frac{\alpha\beta}{3})^{\frac{1}{1-\alpha}} \frac{1}{2\omega_1}$. Note that $\frac{\partial^2 \Delta^{RD}(\omega_1)}{\partial r^2} < 0$; hence, below r^{RD} increasing the harvest fraction increases $\Delta^{RD}(\omega_1)$ and therefore ω^{RD} , and above the critical level increasing r decreases the risk-dominance threshold. Furthermore, comparison of r^{RD} with the critical harvest fraction of $\underline{\Delta}^0(\omega_1)$ implies $\bar{r} < r^{RD}$.

5 Imprecise Assessments

Under precise information the fishing countries could perfectly anticipate the harvesting decision of the other country in equilibrium.¹⁵ However, in reality the harvesting countries do not share either precise or common information about the stock of the resource. In this section another layer of uncertainty is introduced to the analysis, and the model is examined under the more plausible assumption that the fishing countries do not assess the state of the environment precisely in any period but obtain the public signal, y_t , and the private signals, x_t^i , which are subject to measurement errors. Since the private signals about the stock of the fishery are highly correlated between the two countries, each signal conveys some information about the signal of the other country, and therefore about its action. On the other hand, this information is noisy and leads to strategic uncertainty and the possibility of coordination failure. In such an environment, in which the countries face both biological and strategic uncertainties, they form higher-order beliefs about each other's beliefs about the stock of fish.

5.1 Equilibria with Imprecise Assessments

Before characterising the equilibrium strategies, let us examine the probability of sustainable yield given private and noisy information. I assume there exist levels of fish stock such that $\underline{\omega}_1 - 2a > 0$ and $\bar{\omega}_1 + 2a < 1$. Now if country i observes a signal $x_1^i < \underline{\omega}_1 - a$, then it believes that $\omega_1 < \underline{\omega}_1$. So that regardless of its belief about the other country, it chooses sustainable harvest with probability one, as a dominant strategy. If any country has a private assessment $x_1^i < \underline{\omega}_1 - 2a$, then it believes that the other country is definitely receiving a signal $x_1^{-i} < \underline{\omega}_1$. Hence, for any $\omega_1 < \underline{\omega}_1 - 2a$, the probability of (S, S) is one. By the same argument, in the UDR, for any $\omega_1 > \bar{\omega}_1 + 2a$, the probability of (S, S) is zero. If $\omega_1 \geq \underline{\omega}_1$, no country has an assessment $x_1^i < \underline{\omega}_1 - a$. Likewise, where $\omega_1 \leq \bar{\omega}_1$, neither of them have a signal $x_1^i > \bar{\omega}_1 + a$. Thus, for any $\omega_1 \in [\underline{\omega}_1, \bar{\omega}_1]$, there is no dominant strategy and the countries' beliefs about each other determine the probability of (S, S) , and it varies between its upper bound (one) and its lower bound (zero). Therefore, in the

¹⁵ This is despite the fact that it cannot be predicted which equilibrium is selected.

absence of any equilibrium refinement, there is a multiplicity of equilibria in the intermediate region.

Furthermore, it can be deduced that overfishing in the first period may occur for two reasons. First, the private noisy assessment of the resource may provide some information that overfishing is a dominant action in that region. For example, if the stock of resource in the first period is above $\bar{\omega}_1 + 2a$, then overfishing happens because the countries observe high signals about the stock (where the fishery has a low reproduction and overfishing cost is relatively low).

In addition, the correlated assessments convey noisy information regarding the assessment and hence too the belief of the other country. Thus overfishing may happen because a country believes that the other country has observed a high signal, although its own assessment does not imply that the fishery is in the UDR. In other words, under the strategic-uncertainty assumption, the coastal states try to second-guess each other's harvesting action. So, if they believe that assessment of the other country may lead to its overfishing, then overfishing is a best response and it leads to the depletion of a fishery which may not be in the UDR. Recall that in the intermediate region it is not dominant to overfish, and the countries try to coordinate their harvesting actions by forming higher-order beliefs about each other's assessments. Simply a negative belief about the assessment of the other country can trigger the overfishing and hence the collapse of the fishery in the first period.

In the intermediate region of $[\omega_1, \bar{\omega}_1]$, the fear of miscoordination on the equilibrium path, which translates to 'pessimism' about the possibility of unilateral overfishing by the other country, is the result of observing noisy private signals.¹⁶ I refer to overfishing in the intermediate region as 'panic-based' overfishing,¹⁷ when it is the result of pessimism about the belief of the other harvesting country. With imprecise signals the intermediate region may include a large range of different sizes of the biomass.

It should be noted that the formation of higher-order beliefs and the existence of strategic uncertainty under imprecise private information is independent of the number of periods in the model. However, the particular threshold that is derived in the next section depends on the assumption that at the end of the second period the stock collapses because of the ecological variabilities. Furthermore, in any finite-horizon extension of the model the threshold-strategy behaviour of harvesters could be expected, as long as the expected payoffs of a given period have single crossing.

Because the signals affect the countries' beliefs about both the state of the fishery and the action of the other country, the expected payoff of countries and hence their equilibrium actions depend on their private assessments. To find the equilibrium strategies, again each country compares the expected payoffs of sustainable fishing and overfishing, which depend on its own belief about the stock of the fishery, in addition to its belief about the belief of the other country about the state. Let $\Delta^i(\omega_1, x_1^{-i}(x_1^i, y_1) \mid x_1^i, y_1)$ be the difference of expected payoff of sustainable fishing versus overfishing for country i in period 1, given the observed signals and its belief about x_1^{-i} . In other words,

¹⁶ The term 'fear of miscoordination' is borrowed from Chassang (2010), who explains that although the probability of actual miscoordination in the equilibrium of a global game is very small, the 'fear' of miscoordination influences the equilibrium actions.

¹⁷ The term 'panic-based' action is also borrowed from the bank run paper of Goldstein and Pauzner (2005) on the literature of global games.

$$\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid x_1^i, y_1) \equiv \mathbb{E} \left[\left(r\omega_1 + \frac{\beta}{2}\omega_2 \right) \mathbf{1}_{\substack{\sigma_1^i=1 \\ \sigma_1^{-i}=1}} + (r\omega_1) \mathbf{1}_{\substack{\sigma_1^i=1 \\ \sigma_1^{-i}=0}} - \left((1-r)\omega_1 - \frac{\kappa}{\omega_1} \right) \mathbf{1}_{\substack{\sigma_1^i=0 \\ \sigma_1^{-i}=1}} - \left(\frac{\omega_1}{2} - \frac{\kappa}{\omega_1} \right) \mathbf{1}_{\substack{\sigma_1^i=0 \\ \sigma_1^{-i}=0}} \middle| x_1^i, y_1 \right] \quad (5.1)$$

where $\mathbf{1}_\chi$ is the indicator function, which is 1, if χ is satisfied and is 0 if not.

In an environment where the countries cannot assess the stock of the fishery absolutely precisely, the expected payoffs in (5.1) and the conditional probability of the assessment of the other country are difficult to work out. In Appendix 7.3 the conditional probability densities of the stock and the belief of the harvesting partner for uniform (non-vanishing) noise are derived. These are the main ingredients of analysing the model under the assumption of non-vanishing noise.

5.2 Equilibrium Refinement with Imprecise Assessments

Carlsson and Van Damme (1993) and Morris and Shin (1998) provide a tractable equilibrium-refinement method, which ends up with selection of a simple threshold-form equilibrium. Under this equilibrium, the agents compare their private assessments with the common threshold and choose a unique action. Their analysis investigates the limit case where the private information is ‘almost’ precise ($a \rightarrow 0$), although the state variable will never become common knowledge. Given the possibility of coastal states’ accessing almost precise assessment technologies I focus here on the global-game equilibrium selection.

Under almost precise information, where the noise of the private signal becomes vanishingly small, I claim there exists a symmetric equilibrium threshold, ω^* . If there exists such a threshold Perfect Bayes Nash equilibrium (PBNE), then in equilibrium, country i by observing a signal below $\omega^* - a$ (above $\omega^* + a$), chooses sustainable fishing, i.e. $\sigma_1^i = 1$, (overfishing, i.e. $\sigma_1^i = 0$), where $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid x_1^i, y_1)$ is positive (negative) for that country. Furthermore, if the country receives exactly the critical signal of $x_1^i = \omega^*$, then country i must be indifferent between sustainable fishing and overfishing in equilibrium, i.e. $0 \leq \sigma_1^i \leq 1$. Hence, given the properties of the expected payoff function, examined in “Appendix 7.4”, a sufficient condition for the existence of a threshold PBNE is $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*, y_1) = 0$.

In equilibrium both countries choose the same level of harvest unless the countries observe signals which are very close to the critical signal, i.e. $x_1^i \in [\omega^* - a, \omega^* + a]$, and their signals happen to be from the two sides of the threshold. In such a case, miscoordination happens on the equilibrium path. This chaos is rare, but with noisy private information, it happens around the equilibrium threshold with a vanishingly small probability. This provides a possible explanation of the observed heterogeneity of fishing activities in some shared fisheries: for example, some countries impose targets to stop overfishing, but in the same fishery some other countries have significantly larger fishing fleets.

The result of this equilibrium selection is summarised in the next proposition and the proof is provided in Appendix 7.4.

Proposition 2 *Under private information, there exists $\bar{a} > 0$ such that for all $a < \bar{a}$ in the first period of any game in G there exists a unique equilibrium which admits a symmetric PBNE threshold, ω^* , such that country i , for any signal $x_1^i < \omega^* - a$, fishes sustainably and for $x_1^i > \omega^* + a$, chooses overfishing.*

Given the unique threshold, ω^* , it is the best response for both countries to follow the described strategies for any level of the signals. More precisely, in the limit,¹⁸ if the private assessment of country i is above ω^* , the country infers that the fishery is not highly productive and that the overfishing cost is relatively low, then it should have more incentive to overfish. In addition, its highly correlated private information with the signal of the other country implies that the other country is also likely to choose overfishing and given the strategic complementarity in the payoffs, overfishing is reinforced. Therefore, for any $x_1^i > \omega^* + a$, $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid x_1^i)$ is negative and overfishing is chosen in equilibrium. By a similar argument, for a country with an assessment below the critical level, i.e. where $x_1^i < \omega^* - a$, the expected payoff differential is positive; hence it chooses sustainable fishing.

Apart from the region very close to the threshold, the probability that the two countries obtain private signals from the two sides of the threshold converges to zero, as the noise of private signal converges to zero, although they do not know the ranking of their signals. Thus, for any level of stock $\omega_1 \in (0, \omega^* - a)$ the probability of overfishing is zero, and for any $\omega_1 \in (\omega^* + a, 1)$ the probability of overfishing is one. If $\omega_1 \in [\omega^* - a, \omega^* + a]$, the probability of overfishing belongs to $[0, 1]$. Note that these probabilities are independent of the specification of upper-bound and lower-bound thresholds, though their existence is important in deriving the uniqueness result.

It is the dominance solvability of global games which rules out any equilibrium other than the monotone strategies and leads to the uniqueness of the described threshold-equilibrium PBNE. Intuitively, as explained, if country i obtains an assessment from the LDR, i.e. if $x_1^i < \underline{\omega}_1 - a$, overfishing is strictly dominated. Knowing that the other country has the same strategy for such a level of observation of biomass, if country i receives a signal slightly to the right of this range, i.e. $\underline{\omega}_1 - a < x_1^i < \underline{\omega}_1 - a + \eta$, for a small η , it believes that in such a situation the other country would be more likely to choose the sustainable harvest as a dominant action, so that $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid x_1^i)$ would be positive. This leads to another round of deletion of strictly dominated strategies. By continuity, the same argument goes for $\underline{\omega}_1 - a < x_1^i < \underline{\omega}_1 - a + 2\eta$, and the iterated deletion goes on. This pattern of argument also starts from UDR and both deletion processes cease around the threshold. It is the existence of dominance regions which ignites this ‘contagious effect’, and results in a unique prediction for any level of fish stock.

The fact that the equilibrium is the unique strategy that survived iterated deletion of strictly dominated strategies implies that the harvesting agents need not have common expectations about each other’s strategies in equilibrium. By assuming almost precise private information, rationality of harvesting agents automatically enforces the unique monotone strategy of global games. Therefore, it is sufficient to assume rationality and common knowledge of rationality to justify the choice of the global game equilibrium-refinement criterion.

In Appendix 7.5, it is shown that the global-game analysis is independent of the distribution of noise and prior, because locally any distribution is uniform. This provides an added value to the theory in the pathway of policy contribution.

Finally, the results are independent of the precision of the public signal, c , when $c > a$. In fact, when the private assessments are extremely informative, the countries ignore their prior beliefs and the public signal.

¹⁸ Note that by the limit, I refer to the unique equilibrium for all a sufficiently small, and not to the uniqueness of the limit of equilibrium strategies.

5.3 Selection of Risk-Dominant Actions with Imprecise Private Information

The global-game threshold coincides with the risk-dominant threshold of the precise-signal case.¹⁹ Indeed, the predictions of the two models are similar, although in global games it is the private signal (rather than simply the stock) which determines the unique equilibrium action. And so the harvesters on the global-game equilibrium will always coordinate on the less-risky action. As explained by Carlsson and Van Damme (1993), the rationality assumption leads to the selection of the risk-dominance equilibrium, and it provides a justification for the selection of the less risky actions in equilibrium suggested by Harsanyi and Selten (1988). Therefore, given advances in the assessment of the stock of fisheries, selection of the global game criterion is not a matter of choice by the researcher, and the unique PBNE of global games is not the result of the application of an equilibrium-selection technique; rather the rationality of harvesters enforces it.

Intuitively, under the biological and strategic uncertainties, the harvesting countries prefer the risk-dominant actions where their beliefs about the state of the fishery and their inferred information about the other country are consistent with their beliefs in the dominance regions. This (non-arbitrary) coincidence of thresholds has particularly interesting for policy implications. The dominance solvability only requires the assumption of rationality and the formation of higher-order beliefs by the coastal states (in comparison to the equilibrium that would also need common expectations and Bayesian updating of the policy makers). Hence, according to this coordination model under almost precise information, although the harvesters acquire asymmetric assessments, the strategic uncertainty is not a major issue for the fishery research institutes. Using the risk-dominant threshold of the precise-signal situation is the simplest way of deriving the unique prediction about the rational behaviour of countries.

Lastly, as mentioned in Sect. 4, without the overfishing cost there would not be any LDR, but the game would have a unique threshold-form PBNE, since $\Delta^{RD}(\omega_1)$ would admit a single crossing; and Proposition 2 would hold. In other words, monotonicity of $\Delta^{RD}(\omega_1)$ is a sufficient condition for the uniqueness of the threshold, but not a necessary condition. However, lack of the LDR implies that the unique monotone-strategy PBNE would not be necessarily the unique strategy that survives the iterated deletion of strictly dominated strategies, and therefore the game would not necessarily have a unique equilibrium.

5.4 Optimal Policy

If information is almost precise, the comparative static result of the risk-dominant threshold can be applied to the case of imprecise assessments. In this subsection, I focus on the contribution of the results to the policy-related parameters: the overfishing cost parameter, κ , and the harvest fraction of sustainable fishing, r .

As discussed, the increase in the cost of illegal fishing increases the lower-bound, the upper-bound, the risk-dominance and consequently the global-game thresholds. Hence, according to the model, no matter whether the harvesting countries are affected by biological or strategic uncertainties, increasing the overfishing cost makes the fishery unambiguously less vulnerable to overfishing either as a dominant action or as a panic-based harvest.

In contrast to the overfishing cost, expected payoff differential (and therefore ω^*) is not monotone in the harvest fraction. When the information becomes almost precise, the RFMOs may target the critical TAC corresponding to the maximum threshold, r^{RD} , to ensure the largest conservation threshold under public and private information scenarios.

¹⁹ See the characterisation of equilibrium in Appendix 7.4.

However, the optimal policy level of overfishing cost and the harvest fraction of sustainable yield may not necessarily target the maximum conservation threshold. Different institutional frameworks in international fishery agreements may affect the determination of the two variables. In the intergovernmental negotiations about these policy variables, the countries may balance the conservation incentives and the overfishing temptation. Here as an alternative, the optimal policy variables are derived such that maximisation of the net payoff of a representative country is targeted.

If the countries assess the fisheries privately and sufficiently precisely, the probability of miscoordination vanishes. Hence, for practical implementation it is possible to exclude the payoffs of miscoordination from the net payoff in (5.1). Therefore, the optimal policy can be obtained by maximising the net benefit of a representative country on the equilibrium path, $B(\kappa, r)$, where

$$B(\kappa, r) \equiv \int_0^{\omega^{RD}(\kappa, r)} [rw_1 + \frac{\beta}{2}b\omega_1^\alpha]f_{\Omega_1}(\omega_1 | x_1^i)dw_1 + \int_{\omega^{RD}(\kappa, r)}^1 [\frac{\omega_1}{2} - \frac{\kappa}{\omega_1}]f_{\Omega_1}(\omega_1 | x_1^i)dw_1 \quad (5.2)$$

The heterogeneity in the model is due to private assessment of the fishery, and when the correlated information of coastal states becomes almost precise, it becomes possible to focus on the representative country. Again, note that the convenient risk-dominance threshold of precise information is used for policy making. In other words, knowing that for all levels of fish population below the risk-dominant (and PBNE) threshold, both countries harvest sustainably and above it, they both overfish, it is possible to uniquely define the equilibrium net benefit of the countries as specified in (5.2). Therefore, simply $\frac{\partial B(\kappa, r)}{\partial \kappa} = 0$ and $\frac{\partial B(\kappa, r)}{\partial r} = 0$ are the necessary conditions of the optimal overfishing cost and harvest fraction, respectively. Hence, if κ and r are treated as variables which can be set optimally, it is possible to gain from the equilibrium-selection results, and from point of view of a country which maximises its payoff, these necessary conditions provide the optimal policy levels of the overfishing cost and the harvest fraction.

6 Conclusions

This paper set out to find a possible reason for failure to observe bilateral harvesting agreements in transboundary fisheries. The theoretical framework suggests that private information acquisition results in the risk of miscoordination. This may induce pessimism about the sustainability of the resource, which rationally can increase the temptation to overfish. Furthermore, under sufficiently precise private information, and its resulting equilibrium refinement, the paper derives the unique probability of overfishing at each level of the (assessment about the) stock of the fishery.

According to the 1982 UN convention, coastal states sharing a transboundary fishery are asked to coordinate on its management and conservation. Despite the fact that countries acquire public and private assessments about fisheries, the outcome of intergovernmental negotiations does not necessarily lead to the formation of an international fishery agreement. Furthermore, when there are international treaties, there is no guarantee of their sustainability. This is consistent with the prediction of this paper that the countries sometimes choose precautionary harvest and compliance with the terms of such agreements, but sometimes they choose overfishing as a risk-dominant action.

An example is the management of fisheries shared between Norway and U.S.S.R./Russia: according to Armstrong (1994) and the Seafish (2017), for more than 50 years the parties

have been both carrying out independent scientific stock assessment and obtaining data from international fishery institutions. Over this period the two countries have been successful in conserving their cod fisheries under the North East Arctic Cod Fishery, today known as the Joint Russian–Norwegian Fisheries Commission (JR-NFC). The stock is considered to be low-risk stock with precautionary harvest.²⁰ On the other hand, these two countries were not successful in coordinating management of capelin in the Barent Sea, and the stock collapsed twice in the 1980s and 1990s. As explained, the cooperation of Canada and the United States on their salmon stocks has also been through challenges at various stages. Of course, in both of these examples, the ecological factors compounded the exhaustion problem.

If it can be assumed that the rational policy makers are able to form higher-order beliefs, the paper suggests a unique prediction about the fate of the bilateral fishing agreement, under almost precise information. Then the outcome of the model with strategic uncertainty is reduced to the outcome of the symmetric-information game, which is implied by the equivalence of risk-dominant and global-game equilibrium thresholds. Furthermore, relative to PBNE, the dominance solvability requires less restrictive assumptions. These results contribute to considerable tractability in the derivation of optimal policy variables in trans-boundary fisheries.

Specifically, the study emphasises the overfishing cost and the TAC, as policy instruments. Finding the optimal level of TAC can have implications for common forms of this instrument in fishery management, such as quotas, individual transferable quotas and Territorial Use Rights for Fishing (TURF). The study suggests that the risk-dominant threshold is increasing in TAC up to a critical level of this parameter.

In addition, the analysis shows that the risk-dominant threshold of sustainable harvest is monotonically increasing in overfishing cost. This is the cost of breaching the international fishery agreement and is positively related to public awareness. International campaigns and NGOs can play an important role in the provision of information to the public regarding the sustainability of harvests. Hence, better monitoring and transparency of harvest in trans-boundary fisheries increases the overfishing cost. This can be addressed by recent advances in technology and the universal use of satellite imaging data such as Global Fishing Watch data.²¹ In addition, more cooperation by the international legislative institutions is needed. For example strict tracking requirements could be set by international insurance organisations to improve transparency of harvest.

A worthwhile future research direction in the context of policy implication would be investigating the effect of endogenising information acquisition. In this paper, the precision of the private information is exogenous. However, in line with the study on costly information acquisition in global games by Szkup and Trevino (2015), this assumption can be relaxed. Szkup and Trevino derive the socially efficient amount of private information to be acquired and check whether there are strategic complementarities in information acquisition. In our context, such a study could help to explain how the precision of the private information can change the probability of overfishing.

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²⁰ Seafish report in 2017.

²¹ <http://globalfishingwatch.org>.

7 Appendix

7.1 Assumptions

Assumption 1 The maximum level of noise of each period, $a + c$, must be small enough relative of the initial stock to guarantee that $x_t^i \in (0, 1)$.

This assumption guarantees that X_t , Y_t and Ω_t map into $(0, 1)$. Since $x_t^i = \omega_t + \varepsilon_t^i$, restricting x_t^i is sufficient and is achieved by assuming $0 < x_1^i < 1$ and $0 < x_2^i < 1$. The first assumption implies

$$(\bar{\omega}_0)^\alpha - c - a > 0 \quad (7.1)$$

$$(\bar{\omega}_0)^\alpha + c + a < 1 \quad (7.2)$$

and the second implies

$$b[(\bar{\omega}_0)^\alpha - c]^\alpha - c - a > 0 \quad (7.3)$$

$$b[(\bar{\omega}_0)^\alpha + c]^\alpha + c + a < 1 \quad (7.4)$$

where $b \equiv (1 - 2r)^\alpha$. These four conditions can be summarised as follows:

$$a + c < \min \left\{ (\bar{\omega}_0)^\alpha, 1 - (\bar{\omega}_0)^\alpha, b[(\bar{\omega}_0)^\alpha - c]^\alpha, 1 - b[(\bar{\omega}_0)^\alpha - c]^\alpha \right\} \quad (7.5)$$

Assumption 2 Game G is such that for all $\omega_1 \in (0, 1)$, $\frac{\partial \underline{\Delta}^0(\omega_1)}{\partial \omega_1} < 0$, furthermore $\underline{\Delta}^0(\omega_1 = 1) < 0$.

Note that $\underline{\Delta}^0(\omega_1)$ is a strictly decreasing function with respect to ω_1 if $\frac{\partial \underline{\Delta}^0(\omega_1)}{\partial \omega_1} = \frac{\beta}{2} b \alpha \omega_1^{\alpha-1} - (1 - 2r) - \frac{\kappa}{\omega_1^2} < 0$. This is satisfied if and only if $\frac{\beta}{2} b \alpha \omega_1^{\alpha+1} - b^{\frac{1}{\alpha}} \omega_1^2 < \kappa$. Recall that $\underline{\Delta}^0(\omega_1)$ is the expected payoff differential of a country where the other country is harvesting sustainably. Hence this assumption requires that the overfishing cost parameter, κ , is large enough that if the other country harvests sustainably, then the marginal benefits of fishing sustainably in the form of future growth ($\frac{\beta}{2} b \alpha \omega_1^{\alpha-1}$) are outweighed by the marginal net benefit of breaching the agreement ($(1 - 2r) + \frac{\kappa}{\omega_1^2}$). In other words, the marginal *net* benefit of sustainable harvesting is decreasing, upon sustainable harvest by the other country.²² Furthermore, if the LHS of the inequality is negative, then this assumption is reduced to $\kappa > 0$.

In addition, $\underline{\Delta}^0(\omega_1 = 1) < 0$ reassures the single crossing of $\underline{\Delta}^0(\omega_1)$ in between $(\omega_1, 1)$. Indeed $\underline{\Delta}^0(\omega_1 = 1) = \frac{\beta}{2} b - (1 - 2r) + \kappa$ is negative if and only if $\kappa < (1 - 2r) - \frac{\beta}{2} b$. This can be rewritten as $\frac{\beta}{2} (1 - 2r)^\alpha < (1 - 2r) - \kappa$, which states that κ should be small enough that if the stock is not growing, i.e. $\omega_1 = 1$, then the payoff of catching the left share today, $(1 - 2r) - \kappa$, is greater than the tomorrow's share. Therefore, the two parts of Assumption 2 can be jointly rephrased as

$$\frac{\beta}{2} b \alpha \omega_1^{\alpha+1} - b^{\frac{1}{\alpha}} \omega_1^2 < \kappa < b^{\frac{1}{\alpha}} - \frac{\beta}{2} b \quad (7.6)$$

²² Note that as κ increases, although the benefit of overfishing decreases, the marginal benefit of overfishing, $(1 - r) + \frac{\kappa}{\omega_1^2}$, increases.

Assumption 3 Game G is such that $\underline{\Delta}^0(\omega_1) > 0$.

Recall that ω_1 is defined such that $\bar{\Delta}^0(\omega_1) = 0$. Thus (4.1) and (4.2) imply that Assumption 3 is satisfied if and only if $\frac{2}{b\beta}(\frac{3}{2} - r) < \omega_1^{\alpha-1}$.

7.2 Proof of Proposition 1

Note that $\frac{\partial \Delta^{RD}(\omega_1)}{\partial \omega_1} < 0$ if and only if

$$\frac{1}{2} \left[\frac{\beta}{2} b \alpha \omega_1^{\alpha+1} - b^{\frac{1}{\alpha}} \omega_1^2 - \left(\frac{1}{2} - r \right) \omega_1^2 \right] < \kappa \quad (7.7)$$

The first part of Assumption 2 is sufficient for this inequality to be satisfied, and if the LHS of 7.7 is negative, then $\kappa > 0$ ensures strict monotonicity of $\Delta^{RD}(\omega_1)$. Recall that (4.4) is the sum of $\underline{\Delta}^0(\omega_1)$ and $\bar{\Delta}^0(\omega_1)$. Since $\bar{\Delta}^0(\omega_1 = \bar{\omega}_1) < 0$ and $\underline{\Delta}^0(\omega_1 = \bar{\omega}_1) = 0$, $\Delta^{RD}(\omega_1 = \bar{\omega}_1) < 0$. In addition, $\underline{\Delta}^0(\omega_1) > 0$ and $\bar{\Delta}^0(\omega_1) = 0$ imply that $\Delta^{RD}(\omega_1 = \omega_1) > 0$. Hence, $\Delta^{RD}(\omega_1)$ has a unique real root, say $\omega^{RD} \in (\omega_1, \bar{\omega}_1)$; and the risk-dominant equilibrium admits a threshold form: below ω^{RD} the countries fish sustainably and above it they overfish. \square

7.3 Conditional Probability Density Functions with Imprecise Signals

Recall that $y_t = \omega_t + \theta_t$ and $x_t^i = \omega_t + \varepsilon_t^i$. Let $f_v(\cdot)$ be the probability density function and $F_v(\cdot)$ be the cumulative distribution function of any random variable v . As the main ingredients for analysing the model, I derive the conditional probability density function of the state of the fishery and the signal of the other country for a general noise, i.e. out of the limit.

Since the fishing agents are Bayesian learners, their posterior belief about the state of fishery can be obtained by a simple Bayes rule or the following formula,

$$f_{\Omega_t}(\omega_t | y_t, x_t^i) = \frac{f_{\Theta}(\omega_t - y_t) f_{\varepsilon}(x_t^i - \omega_t)}{\int f_{\Theta}(q - y_t) f_{\varepsilon}(x_t^i - q) dq} \quad (7.8)$$

where the integration variable, q , refers to ω_t . Given that Θ and ε are distributed uniformly, $f_{\Theta}(\omega_t - y_t) = \frac{1}{2c}$ and $f_{\varepsilon}(x_t^i - \omega_t) = \frac{1}{2a}$. Furthermore, support of random variable Ω_t is determined by overlap of two sets: $[x_t^i - a, x_t^i + a]$ and $[y_t - c, y_t + c]$. Therefore, $f_{\Omega_t}(\omega_t | y_t, x_t^i)$ can be written as

$$= \frac{1}{\int_{\max\{y_t - c, x_t^i - a\}}^{\min\{y_t + c, x_t^i + a\}} dq} \quad (7.9)$$

Assuming the private signal to be more precise than the public signal, i.e. if $a < c$,

$$f_{\Omega_t}(\omega_t | y_t, x_t^i) = \begin{cases} \frac{1}{x_t^i + a - y_t + c} & \text{if } \omega_t \in [y_t - c, x_t^i + a] \text{ and } x_t^i - a < y_t - c < x_t^i + a < y_t + c \\ \frac{1}{2a} & \text{if } \omega_t \in [x_t^i - a, x_t^i + a] \text{ and } y_t - c < x_t^i - a < x_t^i + a < y_t + c \\ \frac{1}{y_t + c - x_t^i + a} & \text{if } \omega_t \in [x_t^i - a, y_t + c] \text{ and } y_t - c < x_t^i - a < y_t + c < x_t^i + a \end{cases} \quad (7.10)$$

In addition, from the point of view of player i , the conditional probability density of signal of the other player, X_t^{-i} , can be derived by calculating the convolution of two independent distributions, which is defined as

$$f_{X_t^{-i}}(x_t^{-i} | y_t, x_t^i) = \int f_{\Omega_t}(x_t^{-i} - p | y_t, x_t^i) f_{\varepsilon}(p) dp \quad (7.11)$$

where the integration variable, p , refers to ε_t^{-i} . Thus support of X_t^{-i} is found by overlap of two sets: support of Ω_t and support of ε . Depending on the support of Ω_t , specified in 7.10, the conditional probability density of X_t^{-i} admits three possible cases.

Case I If $\omega_t \in [y_t - c, x_t^i + a]$ and $x_t^i - a < y_t - c < x_t^i + a < y_t + c$,

$$\begin{aligned} f_{X_t^{-i}}(x_t^{-i} | y_t, x_t^i) &= \frac{1}{2a(x_t^i + a - y_t + c)} \int_{\max\{-a, x_t^{-i} - x_t^i - a\}}^{\min\{a, x_t^{-i} - y_t + c\}} dp \\ &= \frac{1}{2a(x_t^i + a - y_t + c)} \begin{cases} x_t^{-i} - y_t + c + a & \text{if } x_t^{-i} \in [y_t - c - a, x_t^i] \\ 2a & \text{if } x_t^{-i} \in [x_t^i, y_t - c + a] \\ 2a - x_t^{-i} + x_t^i & \text{if } x_t^{-i} \in [y_t - c + a, x_t^i + 2a] \end{cases} \end{aligned} \quad (7.12)$$

Case II If $\omega_t \in [x_t^i - a, x_t^i + a]$ and $y_t - c < x_t^i - a < x_t^i + a < y_t + c$,

$$\begin{aligned} f_{X_t^{-i}}(x_t^{-i} | y_t, x_t^i) &= \frac{1}{4a^2} \int_{\max\{-a, x_t^{-i} - x_t^i - a\}}^{\min\{a, x_t^{-i} - x_t^i + a\}} dp \\ &= \frac{1}{4a^2} \begin{cases} x_t^{-i} - x_t^i + 2a & \text{if } x_t^{-i} \in [x_t^i - 2a, x_t^i] \\ x_t^i - x_t^{-i} + 2a & \text{if } x_t^{-i} \in [x_t^i, x_t^i + 2a] \end{cases} \end{aligned} \quad (7.13)$$

Case III If $\omega_t \in [x_t^i - a, y_t + c]$ and $y_t - c < x_t^i - a < y_t + c < x_t^i + a$,

$$\begin{aligned} f_{X_t^{-i}}(x_t^{-i} | y_t, x_t^i) &= \frac{1}{2a(y_t + c - x_t^i + a)} \int_{\max\{-a, x_t^{-i} - y_t - c\}}^{\min\{a, x_t^{-i} - x_t^i + a\}} dp \\ &= \frac{1}{2a(y_t + c - x_t^i + a)} \begin{cases} x_t^{-i} - x_t^i + 2a & \text{if } x_t^{-i} \in [x_t^i - 2a, y_t + c - a] \\ 2a & \text{if } x_t^{-i} \in [y_t + c - a, x_t^i] \\ a - x_t^{-i} + y_t + c & \text{if } x_t^{-i} \in [x_t^i, a + y_t + c] \end{cases} \end{aligned} \quad (7.14)$$

Clearly, case *I* and *III* of $f_{X_t^{-i}}(x_t^{-i} | y_t, x_t^i)$ are trapezoidal distributions and case *II* is a symmetric triangular distribution. All cases are possible, and they can be used in the indifference condition of player i , defined in (5.1).

7.4 Global-Game Analysis with Uniform Noise of the Signals

Before formalising the proof of Proposition 2 assume that country i could observe the stock precisely, but believes that the other country has a private signal x_1^{-i} . From the point of view of such a country, the expected payoff in Eq. (5.1) would be reduced to²³

²³ The implicitly assumed monotone strategy and the uniqueness of threshold are justified later.

$$\begin{aligned} & \Delta^0(\omega_1, x_1^{-i}(\cdot) \mid x_1^i) \\ & \equiv \begin{cases} rw_1 + \frac{\beta}{2}\omega_2 - (1-r)\omega_1 + \frac{\kappa}{\omega_1} & \text{if } x_1^{-i} \leq \omega^* \\ (r - \frac{1}{2})\omega_1 + \frac{\kappa}{\omega_1} & \text{if } x_1^{-i} \geq \omega^* \end{cases} \end{aligned} \quad (7.15)$$

where again superscript 0 refers to the absence of measurement error. Then the probability of sustainable fishing by the other country could be pinned down by

$$Pr(x_1^{-i} < \omega^* \mid \omega_1) = Pr(\omega_1 + \varepsilon_1^{-i} < \omega^* \mid \omega_1) = F(\omega^* - \omega_1 \mid \omega_1) \quad (7.16)$$

where $F(\cdot)$ is the uniform cumulative distribution function of ε_t^i . Hence, if the current level of stock was not a random variable for the countries, but they assume that the other country has private information, it was possible to compute the probability of sustainable fishing or overfishing for any level of the stock. So, $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid x_1^i, y_1)$ in (5.1) would be simply the sum of the expected value of two parts of $\Delta^0(\omega_1, x_1^{-i}(\cdot) \mid x_1^i)$ over the support of x_1^{-i} .

The global-game analysis indeed leads to the tractable analysis of $\mathbb{E}_{x_1^{-i}} \Delta^0(\omega_1, x_1^{-i}(\cdot) \mid x_1^i)$. Notation $\mathbb{E}_{x_1^{-i}}$ emphasises on the fact that uncertainty is reduced to the uncertainty regarding the assessment of country $-i$. First, in equilibrium both countries, which have private assessments about the state of fishery from $[\underline{\omega}_1, \bar{\omega}_1]$, simply solve the problem for a threshold-type player, for whom $\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*, y_1) = 0$; and after deriving the common threshold, ω^* , each country compares its signal with ω^* and chooses an action accordingly.

In the limit that a is sufficiently small, $f_{\Omega_t}(\omega_t \mid y_t, x_t^i) = \frac{1}{2a}$. Hence, I focus on case II of Appendix 7.3, where $\omega_t \in [x_t^i - a, x_t^i + a]$ and $y_t - c < x_t^i - a < x_t^i + a < y_t + c$. Clearly, from the point of view of country i and holding signal x_t^i , the cumulative distribution of signal of the other country will be $F_{X_t^{-i}}(x_t^{-i} \mid x_t^i) = 1 - F_{X_t^{-i}}(x_t^{-i} \mid x_t^i) = \frac{1}{2}$, which translates to holding the Laplacian belief.

From the point of view of the threshold-type country, the stock of fishery in the first period is uniformly distributed over $[\omega^* - a, \omega^* + a]$. Furthermore, vanishing noise leads to a situation where not only the fundamental uncertainty is vanishing, but also the strategic uncertainty is extremely large. Thus, country i with $x_1^i = \omega^*$ would assign uniform probability to the signal of the other country, which is known as holding Laplacian belief. Therefore, for the threshold-type country the expected payoff in (5.1) will be reduced to

$$\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*) = \frac{1}{2a} \int_{\omega^*-a}^{\omega^*+a} \mathbb{E}_{x_1^{-i}} \Delta^0(\omega_1, x_1^{-i}(\cdot) \mid \omega^*) d\omega_1 \quad (7.17)$$

where $\Delta^0(\omega_1, x_1^{-i}(\cdot) \mid \omega^*)$ is defined in (7.15).

Since the two random variables X^{-i} and Ω_1 are highly correlated, all uncertainty can be expressed in terms of strategic uncertainty in the limit that $a \rightarrow 0$, and consequently $\omega_1 \rightarrow \omega^*$. Hence, in the limit

$$\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*) = \mathbb{E}_{x_1^{-i}} \Delta^0(\omega^*, x_1^{-i}(\cdot) \mid \omega^*) \quad (7.18)$$

Furthermore, Laplacian belief about signal of the other country implies

$$\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*) = \frac{1}{2} [2rw^* + \frac{\beta}{2}b(\omega^*)^\alpha - (1-r)\omega^* + \frac{2\kappa}{\omega^*} - \frac{\omega^*}{2}] \quad (7.19)$$

which by definition must be equal to zero. In fact, the term inside the brackets is $\Delta^{RD}(\omega^*)$ defined in (4.4). Thus, the indifference condition of the threshold-type player in the limit

is reduced to $\Delta^{RD}(\omega^*) = 0$, which admits a unique real solution in $(\underline{\omega}_1, \bar{\omega}_1)$, as stated in proposition 1.

After showing the existence of a unique threshold PBNE, in order to preclude any other type of equilibrium, I need to show that threshold-type PBNE is the only strategy surviving iterated deletion of strictly dominated strategy. According to Proposition 2.2 of Morris and Shin (2003), the following conditions are sufficient to show that the characterised threshold-type PBNE satisfies the dominance solvability conditions, and therefore it is the unique equilibrium of the game.

(1) State monotonicity: $\Delta^{RD}(\omega_1)$, which is the sum of $\underline{\Delta}^0(\omega_1)$ and $\bar{\Delta}^0(\omega_1)$, is strictly decreasing in the state of fishery. (2) Action monotonicity: game G is a coordination game and therefore the harvesting levels of countries are strategic complements. (3) Strict Laplacian state monotonicity: for a country with Laplacian belief $\mathbb{E}_{x_1^{-i}} \Delta^0(\omega^*, x_1^{-i}(\cdot) \mid \omega^*)$ has a single crossing at ω^* . (4) Uniform limit dominance: there exists $\underline{x} = \underline{\omega}_1 - a$ such that for all $x_1^i < \underline{x}$, $\Delta^{RD} \geq 0$, and there exists $\bar{x} = \bar{\omega}_1 + a$ such that for all $x_1^i > \bar{x}$, $\Delta^{RD} \leq 0$. (5) Continuity: $\mathbb{E}_{x_1^{-i}} \Delta^0(\omega_1, x_1^{-i}(\cdot) \mid x_1^i)$ is continuous with respect to the signal and probability density of X^{-i} . (6) Finite expectation of signals: the distribution of noise is integrable.

7.5 Characterisation of Global-Game Equilibrium with General Distributions of Noises of Signals

Assume Θ is distributed on $[-c, c]$ and ε is distributed over $[-a, a]$, with probability density functions that are continuous and integrable, but not necessarily uniform.

In contrast to the uniform case, here necessarily the countries in the limit do not have uniform belief about the signal of the other country, but the threshold-type country holds Laplacian belief.²⁴

From the point of view of both countries or the manager of the stock, the country, which would observe the threshold signal, would be the most uncertain country about the action of the other country. Indeed, in the limit of vanishing noise, $Pr(x_1^{-i} < \omega^* \mid \omega^*) = \frac{1}{2}$. Hence, the indifference condition of the threshold-type country, i.e.

$$\Delta^i(\omega_1, x_1^{-i}(\cdot) \mid \omega^*, y_1) = \int_{\omega^*-a}^{\omega^*+a} \mathbb{E}_{x_1^{-i}} \Delta^0(\omega_1, x_1^{-i}(\cdot) \mid \omega^*, y_1) f_{\Omega_1}(\omega_1 \mid \omega^*, y_1) d\omega_1 \quad (7.20)$$

is simplified to $\mathbb{E}_{x_1^{-i}} \Delta^0(\omega^*, x_1^{-i}(\cdot) \mid \omega^*) = 0$ in the limit that Ω_1 and X_1^{-i} are highly correlated. And given Laplacian belief, it is further reduced to $\Delta^{RD}(\omega^*) = 0$.

²⁴ See Appendix B of Morris and Shin (2003) for the proof of Laplacian belief with finite number of players.

7.6 Table of Notation and Definitions

Variable/parameter/function	Description	Range
ω_t	Level of fish stock in period t	$(0, 1)$
y_t	Public signal in period t	$(0, 1)$
x_t^i	Private signal of country i in period t	$(0, 1)$
θ_t	Measurement error of public signal	$[-c, c]$
ε_t^i	Measurement error of private signal of country i in period t	$[-a, a]$
$\bar{\omega}_{t-1}$	Escapement level at the end of period $t - 1$	$(0, 1)$
$\bar{\omega}_0$	Initial stock	$(0, 1)$
σ_t^i	Strategy of country i in period t as the probability of sustainable fishing	$[0, 1]$
α	Growth parameter	$(0, 1)$
β	Discount factor	$(0, 1)$
c	Precision parameter of public signal	$(0, 1)$
a	Precision parameter of private signal	$(0, 1)$
κ	Overfishing cost parameter	See Assumption 2
r	Harvest fraction of each country	$(0, \frac{1}{2})$
$2r$	TAC	$(0, 1)$
b	$(1 - 2r)^\alpha$	
G	The stochastic resource game	
$\bar{\Delta}^0(.)$	Exp. payoff differential of i when $-i$ chooses O, under precise info. in period 1	
$\underline{\Delta}^0(.)$	Exp. payoff differential of i when $-i$ chooses S, under precise info. in period 1	
$\Delta^{RD}(.)$	Risk dominance Exp. payoff differential in period 1	
$\Delta^i(.)$	Exp. payoff differential of i , under imprecise info. in period 1	
Δ^0	Exp. payoff differential of i , with strategic uncertainty, without bio. uncertainty	
$B(.)$	Net benefit of country i	
$\bar{\omega}_1$	UDR threshold	
$\underline{\omega}_1$	LDR threshold	
ω^{RD}	Risk-dominance threshold	
ω^*	Global-game threshold	
$f_v(.)$	Probability density function of any random variable v	
$F_v(.)$	Cumulative distribution function of any random variable v	

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